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**MAGNETIC SUSPENSION CHARACTERISTICS
OF ELECTROMAGNETIC ACTUATORS**

by

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ABSTRACT

Electromagnetic actuators that use a current-carrying coil (which is placed in a magnetic field) to generate mechanical force are conceptually attractive components for active control of rotating shafts. In one concept that is being tested in the laboratory, the control forces from such actuators are applied on the flexibly supported bearing housings of the rotor. Development of this concept into a practical reality requires a clear and thorough understanding of the role of electromechanical parameters of these actuators in delivering the right amount of control force at the right phase into the rotor. The electromechanical parameters of the actuators investigated in this paper are the mass of the armature, stiffness of its suspension, electrical resistance and inductance of the coils. Improper selection of these parameters can result in degradation in their performance, leading to mistuning between the actuator and the rotor. Through a simple analysis, this paper shows that use of such mistuned actuators could result in sharp fluctuations in the phase of the control force delivered into the rotor around the critical speeds. These sharp fluctuations in phase, called "Phase Glitches", are undesirable. Hence, future designs of controllers should take into account the undesirable mistuning effects between the actuator and the rotor caused by the Phase Glitches.

1. INTRODUCTION

Active control of structural vibrations has received considerable attention in the past few decades. Essentially, as shown in Fig. 1, the concept of active control implies that the sensed vibrations are used to generate and apply control forces f_{c1} , f_{c2} , ..., on the structure in such a manner that they either create some favorable characteristics, such as stability, or they counter some undesirable influence of any existing external forces f_1 , f_2 , ... on the structure. The structures whose vibrations are to be controlled can be broadly classified into (a) Stationary Structures, such as Large Space Structures, (b) Moving Structures, such as mechanically levitated Trains or (c) Rotating Structures, such as the shafting in momentum wheels, gyros, compressors, etc. In this paper we restrict ourselves to active control of structures which have one

rotational degree of freedom, such as a compressor rotor or machine tool spindle. There are a number of mechanisms by which control forces could be exerted on these rotating shafts, such as fluid film pressure control, "active-swirl," electro-magnetic forces etc. We focus our attention to only the magnetic or electromagnetic means of force generation. Earnshaw (Ref. 1) has shown that passive suspension of a rotor by magnetic means is unstable, and hence we deal only with active magnetic suspensions herein.

Historically, a number of Control Force Generation Mechanisms that use magnetic means have been examined by various authors with varied degree of success. As summarized by Geary (Ref. 2), most of these mechanisms could be traced directly or indirectly to (a) forces of attraction or repulsion induced solely by magnetic sources, such as electromagnets, permanent magnets, superconducting magnets, diamagnets, ferromagnetic materials, etc., or (b) those induced by interaction between magnetic and electric fields, such as the forces exerted on a current carrying coil that is placed across a magnetic field. The control forces of type (a) will be proportional to the square of the ratio of current and gap (when electromagnets are used) whereas those of type (b) are proportional to the current flowing in the coils. This latter principle of generation of mechanical forces, herein called the Lorentz Force Principle, is most often used in common energy conversion devices such as generators, motors, etc. It is also used in the construction of various vibration excitation devices such as electrodynamic exciters, shakers, linear motors, and electromagnetic actuators. Application of such electromagnetic actuators to control the vibrations of rotors forms the subject matter of this study.

2. ELECTROMAGNETIC ACTUATORS AS CONTROL-FORCE GENERATORS

The electromagnetic actuators have been used recently by Ulbrich (Refs. 3,4) and Nonami (Ref. 5) to actively control the vibrations of an experimental rotating shaft, as shown in Fig. 2. A similar demonstration model has also been reported (Ref. 6) at Case Western Reserve University as a NASA funded activity. In this setup (Fig. 2), the rotor is mounted in two roller bearings. The housings of these roller bearings are flexibly supported from the ground so as to meet the controllability criterion. Electromagnetic actuators symmetrically attached around the housings of these flexibly supported roller bearings deliver the control forces. Thus, the control forces are transmitted into the rotor through the roller bearings. Additional suspensions that support the armature of the actuator are built into the housing of the actuator. A PID type controller generates appropriate control signal using the vibrations of the rotor sensed by some noncontacting type transducer; this control signal is fed into the electromagnetic actuator through power amplifiers to generate the required control forces.

When electromagnetic actuators are so used to generate the control forces, the interaction between the actuator and the rotating structure (rotor) needs to be understood clearly in order to precisely characterize the stability and performance limitations of the closed loop system. This interaction between the actuator and rotor could be broadly classified into (a) Mechanical Interaction that describes the influence of mechanical quantities such as mass of armature m_a , stiffness of its suspension k_a , as well as any mechanical damping in the coil assembly, and (b) electrical interaction that describe the effect of electrical quantities such as resistance R , self inductance L and back emf generated in the electrical circuit that sends in electrical power into the actuator.

3. OBJECTIVES OF THE INVESTIGATION

The mechanical interaction between the electromagnetic actuator (also called 'Linear Momentum Exchange Device' (LMED) or 'Proof Mass Actuator' (PMA) has been analyzed extensively as applied to active control of Large Space Structures (Ref. 7). Basically, it has been shown that damping in the actuator has a beneficial effect in controlling the vibrations of the space structure, but the stroke reversals impose some performance limits on the controller. In a parallel development, the electrical interactive effects have been studied by Rao (Ref. 8) when these actuators are used to excite a structure and measure its frequency response function. Essentially, Rao (Refs. 8,9) has shown that "glitches" (i.e. local variations in the amplitude of force transmitted) could be produced around the structural resonance frequency, and these glitches are influenced by electrical parameters. Review of previous literature (Ref. 8) on the use of exciters in the Experimental Modal Analysis area has established the importance of electromechanical interactive effects between the actuator and the structure as applied to stationary structures. Similar effects are bound to occur when these electromagnetic actuators are used to actively control the vibrations of rotating structure, such as that shown in Fig. 2. But this effect of electrical parameters seems to have not been investigated so far in the literature dealing with active control of rotating structures that use electromagnetic actuators.

The objective of this investigation is, therefore, to identify the electromechanical parameters and analyze their influence on the control force generated and transmitted into the rotor. To this end, we first list the major assumptions of the analysis. We then develop simple coupled equations of motion that include both the mechanical force balance (Newton's laws) and voltage balance (Kirchhoff's laws). We solve these coupled electromechanical equations and determine the control force generated by the actuator on the rotor. We express this control force as a function of nondimensional electromechanical parameters, and then discuss how mistuning between the actuator and the rotor could lead to a phenomenon called "Phase Glitches" around the critical speeds of the rotor.

4. ASSUMPTIONS OF THE ANALYSIS

Since our objective is to understand clearly how both the Mechanical as well as the Electrical parameters of the electromagnetic actuator affect the characteristics of the system, our mathematical model should be simple enough to bring out the essential nature and character of electromechanical interactions but not so complicated that the essence of this electro-mechanical interaction is lost in the complex structural modeling, controller analysis and higher order effects. With this philosophy in mind, we develop a simple mathematical model on the basis of the following assumptions:

1. The mechanical character of the electromagnetic actuator is described by its rigid armature mass m_a and its suspension stiffness k_a . This stiffness k_a includes the stiffness of suspension of the bearing housing as well as the stiffness of suspension of armature. Its mechanical motion is described by a small linear displacement $x(t)$ along the axial

direction of the actuator. These assumptions imply that we neglect all other five degrees of rigid body motion of the armature. We also ignore its internal flexibility and the distributed nature of mass and stiffness of the armature. We also neglect the distributed character of suspension springs. Of particular importance is that we neglect the parasitic motions such as oil canning of the table, micromotions generated by the radiated sound, distortions induced by thermal unbalances, and helical coil effects due to the coils being spread along the length of the armature.

2. The electrical character of this actuator is described by a resistance R (which includes the resistance of coil and any other resistance in the circuit) and self inductance L . We assume that the electrical motion is described by the current $i(t)$. These assumptions imply that we neglect the variations of these quantities with temperature and frequency. We also neglect other parasitic electrical effects like hysteretic losses, eddy currents, I^2R heat loss effects, magnetic saturation effects, internal capacitances and hysteretic losses.
3. We assume that the housing body of the actuator acts as an ideal, infinitely rigid ground that remains stationary while absorbing the reaction force generated in the coils. We further assume that this body does not transmit any part of the reaction force back into the rotating structure through the support platform.
4. We assume that the bearing housing is described with sufficient accuracy by a rigid mass m_b . We thus neglect its flexibility and assume that it acts as a 'simple support' to the rotating structure.
5. We assume that the rotating structure is described by a rigid mass m and complex stiffness k^* . This complex stiffness is expressed as $k^* = k(1 + j\eta)$ where η denotes the structural loss factor of the rotor. They could be its modal or effective values. Implicit in this assumption is that we are dealing with situations when rotor's behavior could be simplistically described by a single degree of freedom.

5. EQUATIONS OF MOTION

Based on the aforementioned assumptions, a simplified model that accounts for both mechanical as well as electrical behavior of the system is shown in Fig. 3. In this model, the electromagnetic actuator's armature is rigidly attached to the bearing housing (m_a denotes the combined effective mass of bearing housing and armature). This actuator's armature is driven by a signal source from a controller through the electrical circuit shown, where R and L denote the effective resistance and self-inductance of the coils. The back emf $k_b \dot{x}_a$ denotes the emf voltage induced into the electrical circuit due to the motion of the coil velocity \dot{x}_a in the magnetic field. Here k_b denotes the back emf constant of proportionality that depends on the flux density. We assume that the energy conversion process is lossless.

The electromagnetic force generated in the coils of the armature is $k_b i$. Some part of this force is 'expended' in overcoming the inertia of the bearing housing and armature mass; another part of it is transmitted into the ground through

the stiff suspension spring; only the remaining part is transmitted into the rotor to control its motion.

Newton's law applied to the mechanical part of the system yields the following equation of motion:

$$\begin{aligned} m \ddot{x} + k^* x + k_b (x - x_a) &= f \\ m_a \ddot{x}_a + k_a x_a + k_b (x_a - x) &= k_b \dot{x} \end{aligned} \quad (1)$$

Similarly, the Kirchhoff's voltage law applied to the electrical circuit yields following voltage balance equation:

$$k_B \dot{x}_a + (R + L d_t) \dot{i} = e(t) \quad (2)$$

Here $e(t)$ denotes the signal voltage generated by the controller and power amplifier combinations that drives the electrical circuit. This could, in practice, depend upon the sensed motion. In PD type of controller, when $e(t)$ will be proportional to the motion x and velocity \dot{x} of the rotor.

Since we want to focus our attention only on the interactive effects between the electromagnetic actuator and the rotor, we make following additional assumptions: (a) the stiffness of roller bearings is very large relative to that of the rotor so that motion of the bearing follows closely that of the rotor, and (b) the rotor is free of synchronous excitations such as unbalances. Under these assumptions, the combined system that consists of the rotor, bearing, and electromagnetic actuator simplifies to that shown in Fig. 4. The equation (2) governing the electrical part remains unaffected by these assumptions. The mechanical part of equation of motion as obtained by Newton's law is modified to:

$$(m + m_a) \ddot{x} + (k^* + k_a) x - k_B \dot{i} = 0 \quad (3)$$

6. EFFECT OF ACTUATOR DYNAMICS ON CRITICAL SPEED

The preceding equation shows that the critical speed of the shaft now will be affected by the mass m_a and stiffness k_a of the actuator. Normally the mass of the armature is negligible. Hence the major parameters influencing the plant's critical speeds are (a) the mass of the bearing housing and, (b) the combined stiffness of the bearing and the armature suspension.

From Eq. (3), it is clear that the performance of the plant is degraded if the natural frequency of the bearing housing mass m_a that is sprung on the suspension stiffness k_a is smaller than the critical speed of the rotor. This condition leads to a reduction in the critical speed of the combined system that consists of rotor, bearing and the electromagnetic actuator (the plant).

Hence it is clear that proper matching of an electromagnetic actuator to the rotor requires that it satisfy the following condition:

$$\frac{k_a}{m_a} \gg \frac{k}{m}$$

When this condition is satisfied, the critical speed of the total system will be higher than the critical speed of the rotor.

7. EFFECT OF ACTUATOR DYNAMICS ON CONTROL FORCE

From equation (3) it is clear that not all of the force ($k_B i$) that is generated in the coils of the actuator is utilized as control force on the rotor. Part of this force is used to overcome the inertia of the bearing housing and armature masses m_a , while part of it is transmitted through the suspension stiffness into the ground. Thus the control force exerted on the rotor is

$$f = k_B i - m_a \ddot{x} - k_a x \quad (4)$$

We assume uniform sinusoidal voltage excitation, $e = e_0 \cos \omega t$, and solve equations (2) and (3) for resulting displacement $x = x_0 \cos \omega t$ and currents $i = i_0 \cos \omega t$ where x_0 and i_0 denotes complex amplitudes. We substitute these amplitudes into (4). We thus arrive at the following expression for the control force as a function of the electromechanical actuator parameters:

$$f_0 = \frac{k^* + k_a}{k^*} \frac{(k^* - \omega^2 m) R}{\{ [k^* + k_a - \omega^2 (m + m_a)] [R + j\omega L] + j\omega k_B^2 \}} \quad (5a)$$

Here f_c denotes the force that would be transmitted into the rotor if it were to be stationary and non-rotating (i.e., $\omega = 0$).

8. IDENTIFICATION OF ELECTROMECHANICAL PARAMETERS OF ACTUATOR

Assuming that the bearing stiffness k_a is negligible relative to the structure's stiffness, the preceding expression for control force could be expressed in nondimensional form as:

$$f_0 = \frac{(1 - \Omega^2 + j\eta)}{\{ (1 - a\Omega^2 + j\eta)(1 + j2\zeta\Omega/k) + j2\zeta\Omega \}} \quad (5b)$$

where the excitation frequency parameter that governs the control force is

$$\Omega = \frac{\omega}{\omega_n} = \frac{\text{excitation frequency}}{\text{critical speed } \sqrt{k/m}}$$

The mechanical parameters influencing the control force are the armature mass parameter, which is defined by

$$M_a = \frac{m_a}{m} = \frac{\text{mass of armature + bearing}}{\text{mass of rotor}}$$

The electrical parameters that influence the control force can be expressed as equivalent mechanical damping and stiffness quantities. They are presented herein as ratios of corresponding rotor's critical damping and stiffness quantities, and are

$$K = \frac{k_B^2/L}{k} = \frac{\text{electrical stiffness of actuator}}{\text{mechanical stiffness of rotor}} \quad (6)$$

$$\zeta = \frac{k_B^2/R}{2\sqrt{k m}} = \frac{\text{electrical damping of actuator}}{\text{critical damping of the rotor}}$$

Further, the quantity a denotes $(1 + M_a)$

9. THE PHENOMENON OF "PHASE GLITCHES"

The importance of mechanical parameters of the actuator has been recognized and analyzed by Zimmerman (Ref. 7) and others in the literature dealing with space structures. However, as shown above, there are electrical parameters that need to be considered before a proper integration between the actuator and the rotor is achieved. Since the mechanical effects have already been well investigated, we analyze now only the effect of electrical parameters of the actuator on the control force around the critical speed.

Fig. 5 shows the variation of amplitude of control force as a function of electrical resistance damping parameter ζ . As can be expected, this figure shows that the control force reaches a maximum value at a frequency called peak frequency (P) which corresponds to the pole in equation (5). This peak frequency is associated thus with the resonance of the total system that consists of the actuator, its electrical circuit, the bearing housing and the rotor. Immediately after this, the force falls sharply to a minimum value at a frequency called notch frequency (N), that corresponds to the zero of Eq. (5). This notch frequency refers to the critical speed of the rotor. This figure also shows that a lower coil resistance (R) increases the electrical damping; this in turn reduces the control force transmitted into the rotor.

Fig. 6 shows how the coil resistance influences the phase of the control force. This diagram shows that the single peak-notch (P-N) present in the previous force-amplitude diagram could possibly be split into two peak-notches on the force-phase diagram. Thus, depending on the value of coil resistance, the phase could show one sharp drop and rise around the peak frequency; or it could show an additional sharp drop and arise around the Notch frequency. These sharp variations in the phase are called herein the "Phase Glitches." These phase glitches are undesirable, and could cause mistuning between the combined

controller circuit and actuator and rotor plant electromechanical system. These possible mistuning effects should be taken into account by future designs of controllers.

The effect of coil inductance on the amplitude of control force is also shown in Fig. 7. As expected, a reduction in the inductance of the coil increases the electrical contribution to the stiffness of the suspension. This increased stiffness implies siphoning of an increased part of force generated by the coils into the suspension, and hence less force is transmitted into the rotor. This results in a reduction in the peak value of the control force as shown in Fig. 7.

Fig. 8 shows the effect of coil inductance on the phase of the control force. As observed above, the phase glitch is present around the critical speed even when inductance is varied. These phase glitches also need to be taken into account in future design of controllers and power amplifiers.

The simplified analysis presented herein has the major aim of emphasizing the fact that a mechanical designer of a magnetic bearing can ill-afford to ignore the electromechanical interactive effects of the actuator. These interactive effects are generated because of electromechanical coupling in the medium that converts the electrical signal into mechanical force. Various approaches are available to address these electromechanical coupling issues and they will be the subject matter of future investigations.

CONCLUSIONS

In this paper we have discussed the conceptual approaches of active control of a rotating shaft's vibrations using electromagnetic actuators. We outlined the basic assumptions normally made in modeling the electrodynamic transduction of the actuator and developed simple equations of motion of a rotor controlled by the electrodynamic actuator through a P-D type feedback. We then derived expression for the control force transmitted into the rotor through the bearing. We showed that this control force displays sharp fluctuations in the phase around the resonance frequency. These fluctuations, called "Phase Glitches," are undesirable. They need to be taken into account in future designs of controllers that use electromagnetic actuators.

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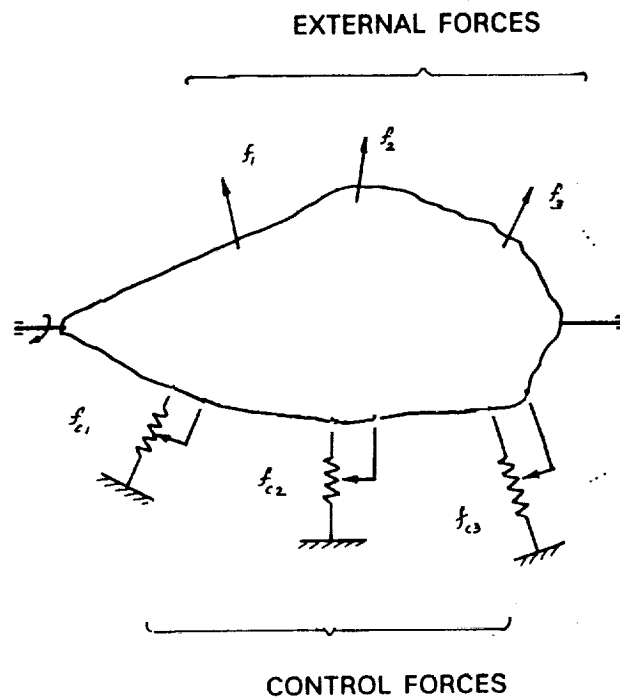


Figure 1. General magnetic suspension problem involves study of response characteristics of an unconstrained structure under external forces and control forces.

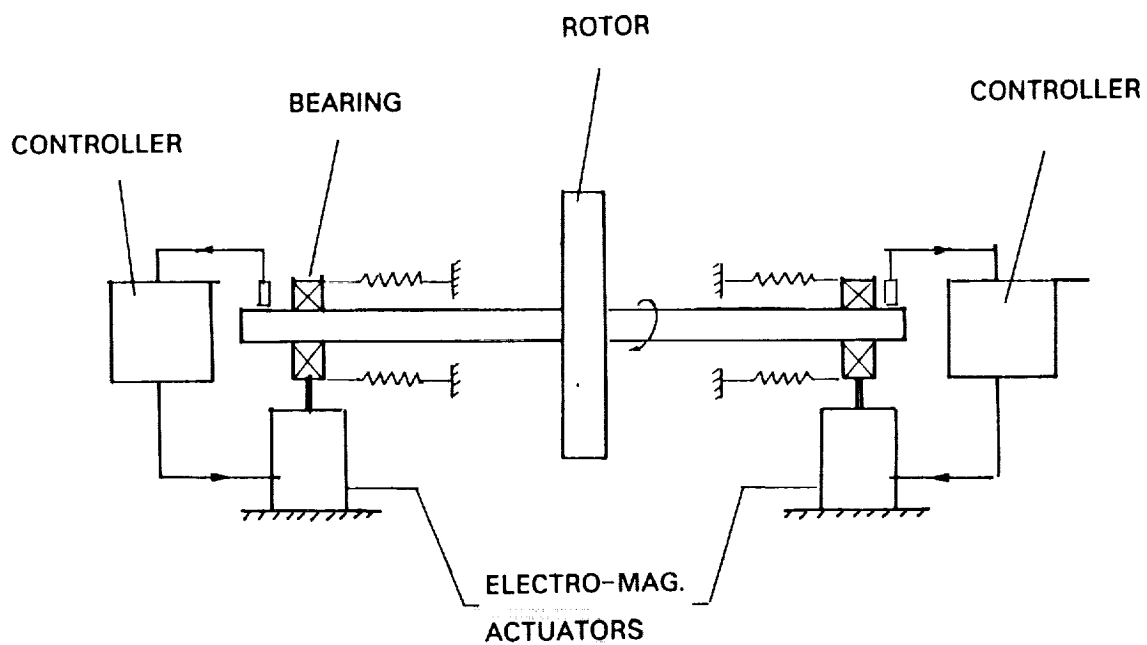


Figure 2. Concept of using electromagnetic actuators to exert control forces on the bearing housing of a rotating shaft.

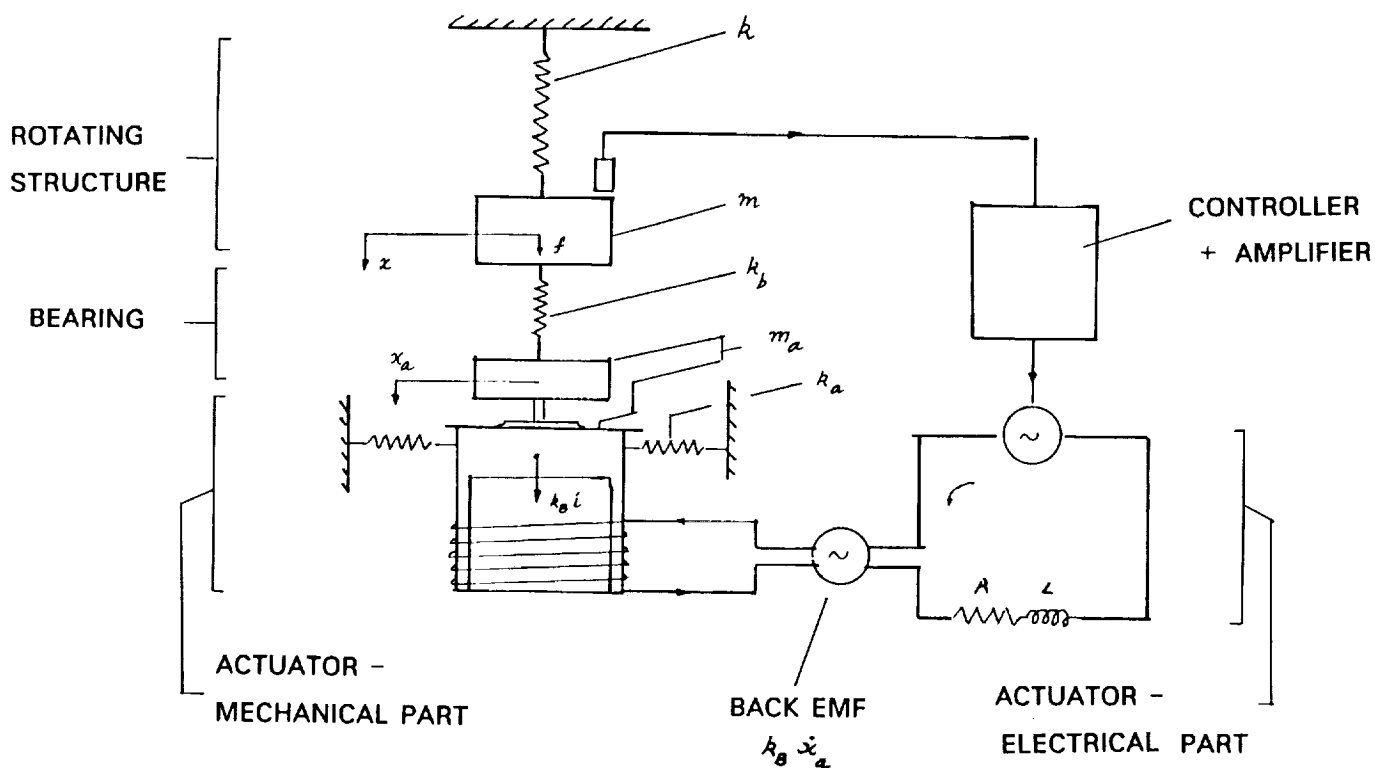


Figure 3. Simplified electromechanical model of an electromagnetic actuator applying control force on the bearing housing of a rotating shaft.

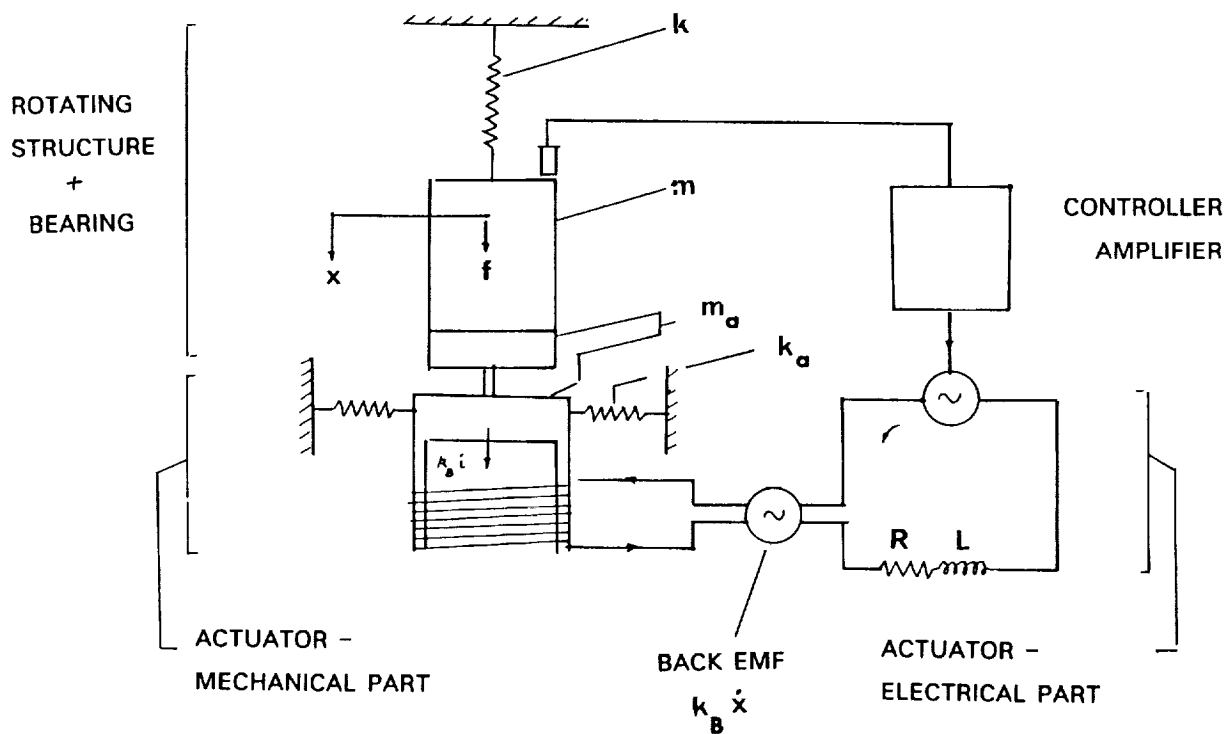
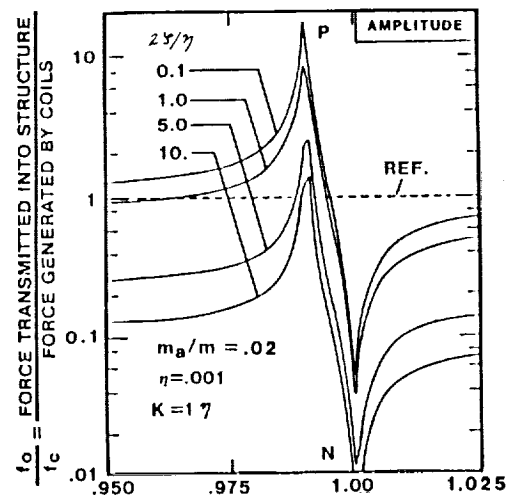
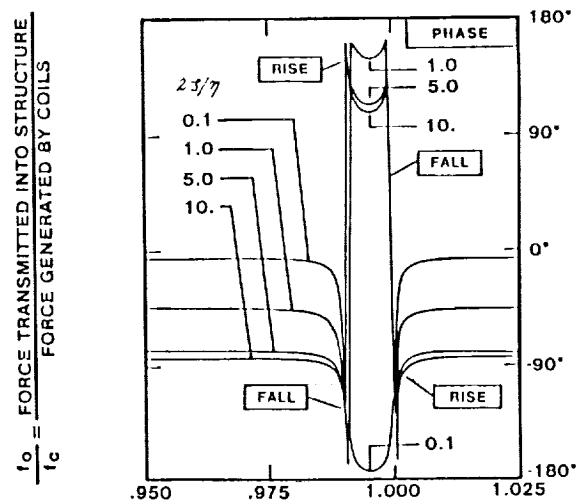


Figure 4. Basic electromechanical model of electromagnetic actuator + rotating structure.



$$\frac{\omega}{\omega_N} = \frac{\text{EXCITATION FREQUENCY}}{\text{NATURAL FREQUENCY}}$$

Figure 5. Effect of coil resistance on the amplitude of control force.



$$\frac{\omega}{\omega_N} = \frac{\text{EXCITATION FREQUENCY}}{\text{NATURAL FREQUENCY}}$$

Figure 6. Effect of coil resistance on the phase of control force.

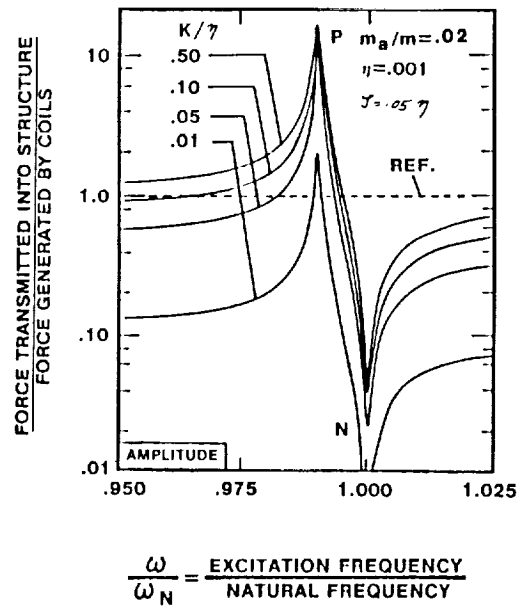


Figure 7. Effect of coil inductance on the amplitude of control force.

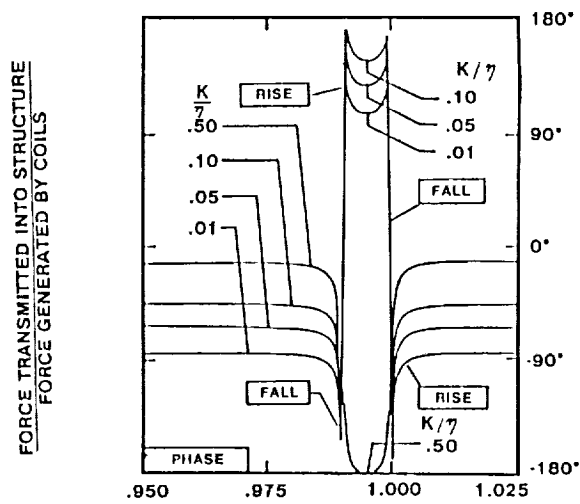


Figure 8. Effect of coil inductance on the phase of control force.

